

# Search for supersymmetric mesinos near production threshold in terms of the superflavor symmetry

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## Abstract

The supersymmetry (SUSY) may be one of the most favorable extensions of the standard model (SM), however, so far at LHC no evidence of the SUSY particles were observed. An obvious question is whether they have already emerged, but escaped from our detection, or do not exist at all. We propose that the future ILC may provide sufficient energy and luminosity to produce SUSY particles as long as they are not too heavy. The superflavor symmetry associates production rates of the SUSY mesinos with that of regular mesons because both of them contain a heavy constituent and a light one. In this work, we estimate the production rate of SUSY mesinos near their production threshold and compare with  $B\bar{B}$  production. Our analysis indicates that if the SUSY mesinos with masses below  $\sqrt{s}/2$  ( $\sqrt{s}$  is the ILC energy) exist, they could be observed at future ILC or even the proposed CEPC in China.

## I. INTRODUCTION

As is well known, the most important goal of high energy research is to look for new physics beyond standard model (BSM), and SUSY may be the most favorable extension of the standard model(SM) because it can reasonably explain the naturalness problem of Higgs and provide a dark matter candidate. Moreover, its existence makes the strong, eletromagnetic and weak interactions to merge into one point at the grand unification scale [1]. However, so far, at Tevatron and LHC, no SUSY particles have ever been observed. One may wonder if the SUSY model is wrong or should be radically modified. Of course, there is one more possibility that the SUSY particles have indeed been produced, but are not identified, namely buried in the messy background at hadron colliders. Several authors [2] notice this possibility and have tried to reanalyze the LHC data and indicated the probability of misidentifying the SUSY particles.

In the minimal supersymmetric standard model (MSSM) and the modified SUSY models, the scalar top quark has two mass eigenstates,  $\tilde{t}_1$  and  $\tilde{t}_2$ , and the lighter one ( $\tilde{t}_1$ ) is assumed to be the lightest squark. Generally, it is believed that the lightest supersymmetric particle (LSP) is the colorless neutralino  $\tilde{\chi}_1^0$ . The present results of the CMS and ATLAS Collaborations for searching scalar top quark can be found in Ref. [3, 4], and it is noted that there is still possibility for stop with mass of a few hundreds of GeV, e.g. there are windows:  $m(\tilde{t}_1) > 200$  GeV with  $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) < m(W)$ , and a heavier stop as  $m(W) < m(\tilde{t}_1) - m(\tilde{\chi}_1^0) < m(t)$ . The literature suggests that considering the 125 GeV Higgs boson observed at LHC, a sub-TeV stop could be allowed by the data [5, 6].

It is also widely recognized that the hadron collider is a machine for discovery, whereas the electron-positron collider is for precise measurement and unambiguous confirmation of discoveries. As long as the SUSY theory or its modified versions are valid and the stop mass is within the energy ranges of LHC and ILC, the stop pair should be produced at those machines with sufficient detection efficiency. At the hadron colliders, the signals of the produced SUSY particles might be buried in the messy background, so one may turn to the electron-positron collider to search for evidence of their existence.

In literature, it is suggested that the squark  $\tilde{t}_1$  is the next-to-lightest supersymmetric particle (NLSP). If the mass of  $\tilde{t}_1$  is not far away from that of LSP, its lifetime could be longer than  $1/\Lambda_{QCD}$  [7–12], and it can attract a SM quark(anti-quark) to form a color singlet SUSY hadron [12–16]: the mesinos after production. For SUSY mesinos consisting of  $\tilde{t}_1$  and a heavy

anti-quark  $\bar{Q}(Q=c,b)$ , the fragmentation functions were calculable through perturbative QCD, and they were studied by Chang et al. [17]. In their scheme, to reliably determine the initial condition for the evolution differential equation, the SM quark must be heavy so that perturbative QCD can apply. Obviously, the production rate for such processes is much suppressed. Whereas, if the SM constituent quark is light (u,d,s) the production rate might be greatly enhanced, however unfortunately then the non-perturbative QCD effects would be dominant, so that the perturbative computation becomes not reliable. An alternative method for evaluating the production rate of such mesinos is needed.

In this work, we focus on the production rate of SUSY mesino which consists of a heavy scalar quark and a light SM antiquark at  $e^+e^-$  colliders. The production rate of a pair of SUSY squark-anti-squark at electron-positron collider have been well calculated at the tree-level and loop-level (see, e.g. [18–20]), thus the key point is how to calculate the hadronic matrix elements which are fully governed by the non-perturbative QCD. Obviously, to directly evaluate the relevant hadronic matrix elements one needs to invoke concrete models. In an interesting scheme we could associate the B-meson production near its threshold which is well measured by CLEO [21], Belle [22], and BaBar [23] collaborations, with the production of SUSY mesinos which may be obtained at ILC near their threshold by means of the superflavor symmetry [24].

The superflavor symmetry establishes a definite relation between the processes involving heavy mesinos and heavy mesons, where both the mesino and meson contain a heavy constituent and a light quark(anti-quark). For the meson case the heavy constituent is a heavy quark(anti-quark) of color-triplet(anti-triplet) fermion  $b(\bar{b})$  or  $c(\bar{c})$ , whereas for the SUSY mesino case the heavy constituent is a color-triplet(anti-triplet) scalar. In our earlier work [25], we supposed the heavy constituent to be a heavy diquark ( $bb$ ,  $bc$  or  $cc$ ) whose inner structure may manifest as a complicated form factor. Of course, it is more natural to apply the theory to the SUSY case where the heavy constituent in the mesino is a point-like color-triplet (anti-triplet) squark (anti-squark). Once we have the relation, we can associate the production rate of the SUSY mesinos at ILC with the measured production rates of the B meson at the B-factories or LHCb.

In the heavy flavor mass limit, the QCD contribution in heavy flavor hadron is independent of the heavy flavor's mass and spin. When we adopt the superflavor symmetry to estimate the production rate of SUSY mesino, the measured B-meson production rate can be obtained simultaneously.

In the ILC technical design report (volume II) [26], the top squark  $\tilde{t}_1$  is expected to be found as long as  $m_{\tilde{t}_1} \leq \sqrt{s}/2$ . At early stage, ILC will be running at  $\sqrt{s} = 500$  GeV with luminosity  $500 \text{ fb}^{-1}$ . In this stage, the  $\tilde{t}_1$  mass will be determined to 1 GeV and even 0.5 GeV accuracy [26, 27]. Then its center of mass energy will be upgraded to 1 TeV with luminosity  $1000 \text{ fb}^{-1}$ . At that energy scale, a SUSY particle with mass less than 0.5 TeV could be found, and if considering possible R-violation, even heavier SUSY particles might be observed.

The work is organized as follows: after this introduction where we explicitly introduce our scheme, we formulate the cross sections for SUSY mesino  $\tilde{X}$  and heavy SM meson  $B$  in terms of superflavor symmetry in Sec. II. In Sec. III, we present our numerical results along with all input parameters, and we especially show how to associate the mesino production with B-meson at B-factories. The last section is devoted to our conclusion and some discussions.

## II. THE SUPERFLAVOR SYMMETRY AND THE SUSY MESINO PRODUCTION

### A. The superflavor symmetry and its application

Let us first have a brief review of the superflavor symmetry, and then focus on its application. Georgi and Wise extended the heavy quark's spin and flavor symmetry and introduced the superflavor symmetry [24]. The superflavor symmetry relates the processes involving a heavy meson made of a heavy quark  $h_v^+$  and a light anti-quark to a heavy fermion (mesino) made of a color triplet scalar  $\chi_v$  (here we suppose it to be a squark) and a light color anti-triplet quark. The lagrangian of the heavy triplets with velocity  $v$  is [24]

$$\mathcal{L}_v = \frac{1}{2}i(\bar{h}_v^+ v_\mu \overleftrightarrow{D}^\mu h_v^+ + 2m_\chi \chi_v^\dagger v_\mu \overleftrightarrow{D}^\mu \chi_v). \quad (1)$$

Putting  $h_v^+$  and  $\chi_v$  altogether into a 5-column vector with a given velocity  $v$ , one has

$$\Psi_v = \begin{pmatrix} h_v^+ \\ \chi_v \end{pmatrix}. \quad (2)$$

Here one can write the wavefunctions of the meson and mesino consisting of  $h_v$  and  $\chi_v$  as

$$\Psi_H(v) = \begin{pmatrix} \sqrt{m_h} \gamma_5 \frac{1}{2}(1 - \not{v}) \\ 0 \end{pmatrix} \quad (3)$$

and

$$\Psi_X(v) = \begin{pmatrix} 0 \\ \frac{u^T C}{\sqrt{2m_\chi}} \end{pmatrix}, \quad (4)$$

where  $C$  is the charge conjugation operator and  $u$  is the spinor wave function of the  $\chi$  bound state.

In the heavy quark effective theory (HQET) [28–30], for the transition of  $b \rightarrow c$ , gluons (or photon) are exchanged at t-channel and the hadronic transition matrix element can be described by a unique Isgur-Wise function  $\xi(\omega)$  where  $\omega = v \cdot v'$  is the recoil variable and  $v, v'$  are the four-velocities of initial and final heavy mesons. For the production process, the gluon, photon or  $Z_0$  (see in the following) is exchanged at s-channel and the kinematic region is different as  $v \rightarrow -v$  [25]. We need to generalize the Isgur-Wise function to the kinematic region of production, and some discussion about this situation was given in Ref. [25].

From the matrix elements of meson and mesino given by Georgi and Wise [24], the corresponding forms at pair production are

$$\langle H(v') \bar{H}(v) | J^\mu | 0 \rangle = \langle H(v') \bar{H}(v) | \bar{h} \gamma^\mu h | 0 \rangle = \xi(-v \cdot v') m_h (v' - v)^\mu, \quad (5)$$

$$\langle X(v') \bar{X}(v) | J^\mu | 0 \rangle = \langle X(v') \bar{X}(v) | i \chi^\dagger \overleftrightarrow{\partial}^\mu \chi | 0 \rangle = \xi(-v \cdot v') \frac{1}{2} (v' - v)^\mu \bar{u}' v, \quad (6)$$

where  $\xi(-v \cdot v')$  is the Isgur-Wise function,  $\xi(1) = 1$  at zero recoil point.

It is natural to apply the superflavor symmetry to SUSY hadron production. In the heavy flavor mass limit, in high energy collisions,  $b\bar{b}$  or stop pairs are produced, and then  $b$  and  $\bar{b}$  or  $\tilde{t}_1$  and  $\bar{\tilde{t}}_1$  hadronize into bound states by attracting antiquark(quark) from vacuum. The two different processes ( $b \rightarrow \text{hadron}$  and  $\tilde{t}_1 \rightarrow \text{SUSY hadron}$ ) can be connected by the superflavor symmetry. Obviously, a heavy quark fragments into a double heavy flavor meson (for example  $b \rightarrow \bar{B}_c(b\bar{c})$ ) is more suppressed compared with a single heavy meson (for example  $b \rightarrow \bar{B}_d(b\bar{d})$ ) by a factor of  $10^{-4} \sim 10^{-3}$  [31]. The case of the SUSY hadron production is similar, i.e. production of mesino  $\tilde{t}_1 \bar{b}(\bar{c})$  is more suppressed than  $\tilde{t}_1 \bar{q}$  ( $q = u, d, s$ ).

A theoretical estimate shows that the so called stoponium can be formed, and the binding energy is about 1-3 GeV [32] which is much smaller than the mass of stop and does not affect the phase space of the production.

Next we calculate the production rate of  $e^+e^- \rightarrow \tilde{X}\bar{\tilde{X}}$  near its threshold at ILC, whose low background makes it more advantageous over hadron colliders.

## B. Estimating the SUSY mesino production rate

To predict the production rate of the SUSY mesinos near threshold, one could associate it with the B-meson production near threshold. Indeed, we wish to use the data of the B-factory to predict the production rates as

$$\frac{\sigma^{theor}(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})}{\sigma(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})} \sim \frac{\sigma^{theor}(e^+e^- \rightarrow B\bar{B})}{\sigma^{exp}(e^+e^- \rightarrow B\bar{B})}, \quad (7)$$

where the superscript "theor" means the theoretically predicted value and  $\sigma^{exp}(e^+e^- \rightarrow B\bar{B})$  is the measured value at B-factories and  $\sigma(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})$  is what we expect. The ratio of

$$\frac{\sigma^{theor}(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})}{\sigma^{theor}(e^+e^- \rightarrow B\bar{B})}$$

can be obtained in terms of the superflavor symmetry, so that one can eventually obtain  $\sigma(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})$ . In fact, by the superflavor symmetry we can relate the matrix element  $\langle \tilde{X}\tilde{\bar{X}} | J^\mu | 0 \rangle$  to the matrix element  $\langle B\bar{B} | J'^\mu | 0 \rangle$ , where  $J^\mu$  and  $J'^\mu$  are vector currents corresponding to squark-anti-squark and quark-anti-quark productions respectively.

However, there is a serious problem that all the available data about the B-meson productions are not exactly what we need, because the available data are from  $e^+e^- \rightarrow \Upsilon(4s)/\Upsilon(5s)/\Upsilon(6s) \rightarrow B\bar{B}$ , namely via the  $\Upsilon$  resonances. Instead, we need the data on the direct production of  $e^+e^- \rightarrow B\bar{B}$ , i.e the contribution of the continuum spectrum near the threshold. The total spectrum on  $R_b$  (defined as  $R_b = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$ ) provided by experimentalists [23] which is close to 0.3 also cannot be used either.<sup>1</sup>

Therefore, we can only associate the production rates of mesino with the B-meson production rates, but so far we cannot use the data to make a definite prediction yet. However, we expect our smart experimental colleagues to figure out an elegant way to extract the continuum contribution from the data or directly measure it in the future (we believe that they will be able to do it), then we will obtain more accurate numerical results of the mesino production rate near threshold.

Below we will derive the transition amplitudes and cross sections for the processes  $e^+e^-$  to  $B\bar{B}$  and  $\tilde{X}\tilde{\bar{X}}$ , where  $B$  and  $\tilde{X}$  denote the meson and mesino respectively. For the process

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<sup>1</sup> For this point, we thank Dr. C.Z. Yuan of IHEP who told us that there are no such data about the continuum spectra available, and also there is no an appropriate way to extract the continuum contribution from the data so far.

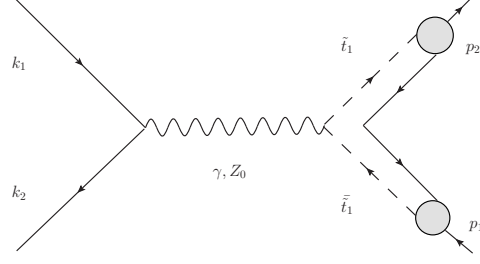
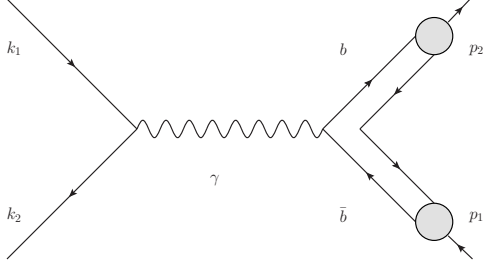


FIG. 1: The process of  $e^+e^- \rightarrow B\bar{B}$ . FIG. 2: The process of  $e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}}$ .

$e^+e^- \rightarrow B\bar{B}$  at B factories, the collision energy  $\sqrt{s}$  is much less than the mass of  $Z_0$ , thus the  $Z_0$  contribution can be safely ignored. By contrast, since in the process  $e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}}$ ,  $\sqrt{s}$  is larger than the mass of  $Z_0$ , the  $Z_0$  contribution must also be included. The differential cross section for B-meson is

$$d\sigma(B\bar{B}) = \frac{1}{8s_1} \sum_{s_i, s_f} \left| \frac{-i}{3} e \langle B\bar{B} | \bar{b} \gamma^\mu b | 0 \rangle \frac{1}{s_1} \langle 0 | \bar{e} (-ie) \gamma_\mu e | e^+ e^- \rangle \right|^2 d\tilde{v}, \quad (8)$$

where only photon contribution is taken into account, and for mesino it is

$$d\sigma(\tilde{X}\tilde{\bar{X}}) = \frac{1}{8s_2} \sum_{s_i, s_f} \left| \frac{2i}{3} e \langle \tilde{X}\tilde{\bar{X}} | \tilde{t}_1^\dagger \overleftrightarrow{\partial}^\mu \tilde{t}_1 | 0 \rangle \frac{1}{s_2} \langle 0 | \bar{e} (-ie) \gamma_\mu e | e^+ e^- \rangle \right. \\ \left. + g_{tz} \langle \tilde{X}\tilde{\bar{X}} | \tilde{t}_1^\dagger \overleftrightarrow{\partial}^\mu \tilde{t}_1 | 0 \rangle \frac{1}{s_2 - m_Z^2} \langle 0 | \bar{e} \gamma_\mu g_{ez} e | e^+ e^- \rangle \right|^2 d\tilde{v}, \quad (9)$$

where  $g_{tz} = \frac{ie}{\sin \theta_w \cos \theta_w} (\frac{1}{2} \cos^2 \theta_t - \frac{2}{3} \sin^2 \theta_w)$  is the coupling constant between stop and  $Z_0$  boson,  $\theta_t$  in  $g_{tz}$  is the stop mixing angle [7],  $\theta_w$  is Weinberg angle,  $g_{ez} = \frac{-ie}{\sin \theta_w \cos \theta_w} (\frac{1-\gamma_5}{4} - \sin^2 \theta_w)$  is the coupling constant between electron and  $Z_0$  boson,  $\sqrt{s_1}$  is the center of mass energy of B factory and  $\sqrt{s_2}$  is the center of mass energy of ILC. It is noted that  $s_i$  is the spin projections of the electron and position in the initial state and  $s_f$  is the spin projections of the produced B mesons or SUSY mesinos in the final state and  $d\tilde{v}$  is the corresponding final state phase space.

Fig.1 and Fig.2 show the leading order Feynman diagrams for the processes  $e^+e^- \rightarrow B\bar{B}$  and  $e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}}$  respectively. The transition amplitudes, for mesons are

$$i\mathcal{M}_B = \xi(-\omega) \left( -i \frac{1}{3} e (p_2 - p_1)_\mu \right) \frac{-i}{s_1} \bar{v}(k_2) (-ie \gamma^\mu) u(k_1), \quad (10)$$

and for mesinos are

$$i\mathcal{M}_{\tilde{X}} = \xi(-\omega) \left[ \bar{u}(p_2) i \frac{2}{3} e \frac{(p_2 - p_1)_\mu}{2m_{\tilde{t}_1}} v(p_1) \frac{-i}{s_2} \bar{v}(k_2) (-ie \gamma^\mu) u(k_1) \right. \\ \left. + \bar{u}(p_2) g_{tz} \frac{(p_2 - p_1)_\mu}{2m_{\tilde{t}_1}} v(p_1) \frac{-i}{s_2 - m_Z^2} \bar{v}(k_2) \gamma_\mu g_{ez} u(k_1) \right]. \quad (11)$$

Here  $\omega = v \cdot v' = \frac{s}{2m^2} - 1$ ,  $k_1$  and  $k_2$  are the momenta of the incoming electron and positron,  $p_1$  and  $p_2$  are the momenta of the outgoing anti-hadron and hadron. It is noted that the hadronic matrix elements are determined according to the superflavor symmetry as shown in Eqs.(5) and (6). Thus we obtain the cross section for pair productions as

$$\sigma = \frac{1}{2s} \int \frac{d^3 p_1}{(2\pi)^3} \frac{1}{2E_1} \frac{d^3 p_2}{(2\pi)^3} \frac{1}{2E_2} (2\pi)^4 \delta^4(p_1 + p_2 - k_1 - k_2) \frac{1}{4} \sum_{spin} |\mathcal{M}|^2. \quad (12)$$

The final expression includes the Isgur-Wise function  $|\xi(-\omega)|^2$  which determines the hadronic matrix elements and manifests the non-perturbative QCD effects in the hadronization. As mentioned above, we cannot use the data to fix the parameters, so generally we will obtain the values of the Isgur-Wise function for certain  $\omega$  by employing some phenomenological models.

### III. NUMERICAL ANALYSIS

So far, the collider experiments including Tevatron and LHC have not set stringent constraints on  $m_{\tilde{t}_1}$  [39, 40] yet, and we would assume  $m_{\tilde{t}_1}$  varying from 200 GeV to 500 GeV.

In our numerical calculation,  $m_B = 5.3$  GeV,  $m_{\tilde{t}_1} = 210 \sim 250$  GeV is taken for  $\sqrt{s} = 500$  GeV and  $m_{\tilde{t}_1} = 420 \sim 500$  GeV for  $\sqrt{s} = 1$  TeV respectively, the running Weinberg angle  $\sin^2 \theta_w$  is taken as  $\sin^2 \theta_w = 0.2398$  for  $\sqrt{s} = 500$  GeV and  $\sin^2 \theta_w = 0.2444$  for  $\sqrt{s} = 1$  TeV,  $\alpha_e$  is approximately equal to  $\alpha_e(m_Z) = 1/128.78$ , the range of mixing angle  $\theta_t$  is uncertain and generally can span in a rather wide range of  $0 \sim \pi$ . Following Ref. [7], in our computation we take a few special values of  $\cos^2 \theta_t$  as 0, 1/2 and 1. Our results obviously depend on the concrete value of  $|\xi(-\omega)|^2$ . We need to extrapolate  $\xi(\omega)$  from a transition region into the annihilation region as  $\omega \rightarrow -\omega$ , and we can write the Isgur-Wise function as

$$\xi(-\omega) = 1 - \rho^2(|\omega| - 1) + c(|\omega| - 1)^2 + \dots, \quad (13)$$

where the parameters  $\rho$  and  $c$  are calculated in the lattice QCD [33].

Many authors have calculated the numerical value  $\xi(\omega)$  in different ways[34–38]. In their articles  $\xi(\omega) < 1$  when  $\omega > 1$ , and all of their results show that  $\xi(1.2) \approx 0.8$ ,  $\xi(1.4) \approx 0.65$ ,  $\xi(1.6) \approx 0.55$  and  $\xi(1.8) \approx 0.5$  for the processes  $B \rightarrow D$ [34–38]. A brief discussion about numerical value of the  $|\xi(-\omega)|^2$  will be given in the next section. In Tab.I and II, we list the production rates of the SUSY mesinos for various  $\omega$ -values.



$\omega$	1.00	1.17	1.36	1.58	1.83
$m_{\tilde{t}_1}$ (GeV)	250	240	230	220	210
$\sigma^{expected}(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})(\text{fb})(\cos^2\theta_t = 0)$	0	0.34	1.33	2.73	4.77
$\sigma^{expected}(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})(\text{fb})(\cos^2\theta_t = 1/2)$	0	0.33	1.28	2.64	4.61
$\sigma^{expected}(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})(\text{fb})(\cos^2\theta_t = 1)$	0	0.50	1.93	3.97	6.94

TABLE I: The cross sections of  $\sigma(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})$  with the center of mass energy  $\sqrt{s}=500$  GeV.

$\omega$	1.00	1.17	1.36	1.58	1.83
$m_{\tilde{t}_1}$ (GeV)	500	480	460	440	420
$\sigma^{expected}(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})(\text{fb})(\cos^2\theta_t = 0)$	0	0.08	0.34	0.69	1.21
$\sigma^{expected}(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})(\text{fb})(\cos^2\theta_t = 1/2)$	0	0.08	0.32	0.65	1.14
$\sigma^{expected}(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})(\text{fb})(\cos^2\theta_t = 1)$	0	0.12	0.46	0.95	1.66

TABLE II: The cross section of  $\sigma(e^+e^- \rightarrow \tilde{X}\tilde{\bar{X}})$  with the center of mass energy  $\sqrt{s}=1$  TeV.

$\omega$	1.00	1.17	1.36	1.58	1.83
$\sqrt{s}$ (GeV)	10.60	11.04	11.52	12.04	12.62
$\sigma(e^+e^- \rightarrow B\bar{B})(\text{pb})$	0	0.94	1.58	1.84	2.06

TABLE III: The cross section of  $\sigma(e^+e^- \rightarrow B\bar{B})$  for the CM energy  $\sqrt{s}$  of the B-factories.

In Tab.I and II we show the numerical values of the cross sections in the range of  $m_{\tilde{t}_1} = 250 \sim 210$  GeV and  $m_{\tilde{t}_1} = 500 \sim 420$  GeV corresponding to  $\omega$  varying from 1 to 1.83 at the center of mass energy  $\sqrt{s} = 500$  GeV and  $\sqrt{s} = 1$  TeV respectively. Tab.III gives the results of  $\sigma(e^+e^- \rightarrow B\bar{B})$  with the same  $\omega$  values as that in Tabs. I, II.

$\omega$	1.00	1.17	1.36	1.58	1.83
$m_{\tilde{t}_1}$ (GeV)	250	240	230	220	210
$\sigma^{theor}(e^+e^- \rightarrow \tilde{t}_1\bar{\tilde{t}}_1)(\text{fb})(\cos^2\theta_t = 0)$	0	3.14	8.62	15.34	22.86
$\sigma^{theor}(e^+e^- \rightarrow \tilde{t}_1\bar{\tilde{t}}_1)(\text{fb})(\cos^2\theta_t = 1/2)$	0	3.04	8.33	14.84	22.12
$\sigma^{theor}(e^+e^- \rightarrow \tilde{t}_1\bar{\tilde{t}}_1)(\text{fb})(\cos^2\theta_t = 1)$	0	4.57	12.54	22.32	33.28

TABLE IV: The cross section of  $\sigma(e^+e^- \rightarrow \tilde{t}_1\bar{\tilde{t}}_1)$  with the center of mass energy  $\sqrt{s}=500$  GeV.

$\omega$	1.00	1.17	1.36	1.58	1.83
$m_{\tilde{t}_1}$ (GeV)	500	480	460	440	420
$\sigma^{theor}(e^+e^- \rightarrow \tilde{t}_1\bar{\tilde{t}}_1)(\text{fb})(\cos^2\theta_t = 0)$	0	0.79	2.18	3.87	5.77
$\sigma^{theor}(e^+e^- \rightarrow \tilde{t}_1\bar{\tilde{t}}_1)(\text{fb})(\cos^2\theta_t = 1/2)$	0	0.75	2.06	3.67	5.47
$\sigma^{theor}(e^+e^- \rightarrow \tilde{t}_1\bar{\tilde{t}}_1)(\text{fb})(\cos^2\theta_t = 1)$	0	1.09	2.99	5.32	7.94

TABLE V: The cross section of  $\sigma(e^+e^- \rightarrow \tilde{t}_1\bar{\tilde{t}}_1)$  with the center of mass energy  $\sqrt{s}=1$  TeV.

In Tab.IV and V we also list the cross sections of the process  $e^+e^- \rightarrow \tilde{t}_1\bar{\tilde{t}}_1$  with the  $m_{\tilde{t}_1}$  varies in the range of  $250 \sim 210$  GeV and  $500 \sim 420$  GeV. The authors of Ref.[19] calculated the cross section and gave its dependence on the CM energy of ILC, while assuming  $m_{\tilde{t}_1}$  to be 200 GeV and 420 GeV respectively. Our results are generally consistent with theirs. From the data above we can find that the ratio of a scalar top quark pair transiting into a SUSY mesino pair is about  $10\% \sim 20\%$ .

#### IV. CONCLUSION AND DISCUSSION

With the help of superflavor symmetry, we associate the production of the stop-mesino pairs with  $B\bar{B}$  near their thresholds. Thus the production rate of the SUSY mesino pair near its production threshold at the future ILC can be compared with the B-meson pair production rate at the B-factories. However, the experimental measurement on the continuum contribution to  $B\bar{B}$  at the B-factory is not available because it is buried in large background corresponding to various resonances which make extraction of the continuum contribution not reliable.

So we use the superflavor symmetry where the non-perturbative QCD effects are included in a unique Isgur-Wise function  $\xi(|\omega|)$  to analyze the mesino production directly. Meanwhile in the same scheme, we also calculate the production rate of  $B\bar{B}$  near its production threshold. The obtained rate is nothing but the continuum contribution to the process  $e^+e^- \rightarrow B\bar{B}$ , and it is a by-product of this research.

From Ref.[34–38] we can find  $\xi(\omega)$  decrease with  $\omega$ , so when  $\omega$  increases, the value of  $|\xi(\omega)|^2$  is less than 1. Therefore, the real production rate of the mesino pair is slightly less than the value we list in Tab.I and II. On the other hand, the heavy quark/squark pair captures a light quark pair from vacuum to form a meson/mesino pair. It means that as the velocity of the heavy quark/squark pair increases, the probability of capturing a light quark pair from vacuum decreases, thus when  $\omega$  increases,  $|\xi(\omega)|^2$  decreases from 1.

The ILC is proposed to begin running in 10 years. Its early stage is designed to be running at the center of mass energy of  $\sqrt{s} = 500$  GeV with yearly integrated luminosity  $500 \text{ fb}^{-1}$ , then the energy will be updated to 1 TeV with the integrated luminosity  $1000 \text{ fb}^{-1}$  [26]. In Tab.VI and Tab.VII we list the numbers of the SUSY stop mesino pairs generated per year at ILC for  $\sqrt{s} = 500$  GeV and  $\sqrt{s} = 1$  TeV respectively.

$\omega$	1.00	1.17	1.36	1.58	1.83
$m_{\tilde{t}_1}$ (GeV)	250	240	230	220	210
events	0	170	665	1365	2385
events	0	165	640	1320	2305
events	0	250	965	1985	3470

TABLE VI: The number of the event predicted in ILC with the center of mass energy  $\sqrt{s}=500$  GeV and luminosity  $500 \text{ fb}^{-1}$ .

Taking into account of detection efficiency there would be a sufficiently large amount of events to be observed.

$\omega$	1.00	1.17	1.36	1.58	1.83
$m_{\tilde{t}_1}$ (GeV)	500	480	460	440	420
events	0	80	340	690	1210
events	0	80	320	650	1140
events	0	120	460	950	1660

TABLE VII: The number of the event predicted in ILC with the center of mass energy  $\sqrt{s}=1$  TeV and luminosity  $1000 \text{ fb}^{-1}$ .

Following suggestions given in literature, we consider the scalar top quark  $\tilde{t}_1$  as the NLSP, thus the mesino which consists of  $\tilde{t}_1$  and a SM anti-quark has very distinctive characters. It is a fermion of baryon number being zero, so it is completely different from the SM baryons. Moreover, as R-parity is conserved, the main decay mode of stop is  $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 + \text{SM quark} (+\text{others})$  where  $\tilde{\chi}_1^0$  is the lightest SUSY particle (LSP): the neutralino. If the mass splitting between stop and neutralino is sufficiently small, the decay channel  $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 + b + W^{(*)}$  is restricted by the final state phase space, Another probable channel would be  $\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 + c(u)$  which occur via loops. so that it is suppressed. The main decay mode of the mesino is via the process where  $\tilde{t}_1$  transits to  $\tilde{\chi}_1^0$  by radiating a SM quark which later combines with the constituent anti-quark (as a spectator) in the mesino to constitute a SM meson (either pseudoscalar or vector). Thus observable process is that a fermion of  $B = 0$  transiting to a SM meson plus missing energy. This signal is very clean and unique, so that from such signal, one can immediately identify the SUSY mesino. Since the stop mesino can be charged ( $\tilde{t}_1 + \bar{d} (\text{or } \bar{s})$ ), one cannot miss its trajectory.

Therefore we expect a stop mesino with a relative long lifetime to be detected at the facilities which will be available in the not-far future. The authors of Ref. [32] also suggested that the stoponium may be observed via its decay products  $\gamma\gamma$  and  $ZZ$  at LHC in the following 14 TeV running. Definitely, they are more easily to be observed at ILC due to its clean background.

Our numerical computations depend on the the Isgur-Wise function which manifests the non-perturbative QCD effects. Since the function is phenomenologically introduced it brings up uncertainties to our numerical results. As we expected, if the continuum contribution to  $e^+e^- \rightarrow B\bar{B}$  could be extracted from the data or directly experimentally measured, we would be able to greatly reduce the theoretical uncertainties and help to draw definite conclusion.

It is also noted that the updated SUSY hadron search results given by CMS [41] and ATLAS

[42] Collaborations indicate that SUSY hadrons' lifetimes should be shorter than  $\mu$ 's if they exist with sub-TeV masses. Indeed, if their lifetimes are too short, it is disadvantageous for their detection, but there still is possibility for direct detection of stop mesinos. We lay hope on the next run of LHC, which may provide information about the SUSY particles, and look forward to the future ILC, where the SUSY particles can be better identified. Moreover, the proposed CEPC (Circular electron-proton collider) and the tera Z-factory in China might also join the project for searching mesinos.

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